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An equivalent thickness conception for prediction of surface fatigue crack growth life and shape evolution

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ABSTRACT

Based on the newly developed equivalent-thickness-based fatigue crack closure evaluation, a surface fatigue crack model is proposed for evaluating the growth rate at each point on the crack border from material base curves obtained by standard straight-through cracked specimens. Using this model, surface fatigue crack propagations in specimens with different initial shapes are predicted through detailed finite element simulations. Good coincidence between the predictions and available experimental results shows that the equivalent thickness conception can serve as a realistic bridge from fatigue crack growth base curves from standard specimens to fatigue crack growth life prediction for three-dimensional engineering structures.

1. Introduction

Material base curves for fatigue crack growth rate are always evaluated through fatigue tests of standard specimens with straight-through cracks and finite thickness. However, damage tolerance and durability of engineering structures come largely from growth of part-through curved crack from initial defects to critical crack size under fatigue loading. Surface fatigue crack growth is the most typical form of damage evolution in engineering structures and has been studied experimentally and numerically for decades [1–5]. As the stress state along the front line of a surface crack changing from the free surface to the interior, the fatigue growth rate of surface cracks should be different along the crack border even bearing the same local stress intensity factor range. For convenience, here we divide the surface crack front line into many sections as shown in Fig. 1. As fatigue crack closure changes along the surface crack front, fatigue crack growth rate at each point i should be different when expressed against the local stress intensity factor range of ΔK_i,

$$\frac{da_i}{dN} = f[\Delta K_i, (K_{op}/K_{max})_i], \quad (1)$$

where da_i and ΔK_i are the local normal crack growth increment and stress intensity factor (SIF) range at point i, respectively; $f(x)$ is the material base curve for fatigue crack growth which can be obtained from fatigue tests on standard specimens; $(K_{op}/K_{max})_i$ is the ratio of opening SIF to the maximum SIF as determined by Yu et al. [6] as a function of local equivalent thickness.

The local stress intensity factor SIF along the front line of a surface crack can be efficiently evaluated by finite element analysis during the fatigue crack growth [1–3]. With the rapid development in computer technology, even a personal

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Nomenclature

a	minor axis of ellipse
B	thickness of plate
B_{eq}	equivalent thickness
c	major axis of ellipse
C_k, n_k	coefficient and power for piecewise Paris law
da/dN	fatigue crack growth rate
E	Young's modulus
H	height of plate
K_{max}	maximum stress intensity factor during a loading cycle
K_{min}	minimum stress intensity factor during a loading cycle
K_{op}	stress intensity factor for crack opening
R	stress ratio
r_p	radius of platic zone
r_{p0}	radius of platic zone for plane stress
t	shape factor of ellipse
T_z	out-of-plane stress concentration factor
W	width of plate
α	plastic-zone-based constraint factor
α_g	global-plastic-zone-based constraint factor
σ_{11}, σ_{22}, σ_{33}	normal stress components in Cartesian coordinates or polar coordinates
σ_0	flow stress
v	elastic Poisson's ratio
v_{ep}	elastic–plastic Poisson's ratio
φ	direction angle of ellipse

computer has become powerful enough for the task to simulate surface crack growth statically with enough fine increment step to provide the stress intensity factor at each step. However, the opening ratio of K_{op}/K_{max} along a surface crack front could not be obtained from fatigue crack growth data of straight-through cracked standard specimens till the work by Yu et al. [6], although a few of experimental efforts have been made to reveal the opening stress ratio along the front line of surface cracks [7].

To extend the equivalent thickness conception proposed by Yu et al. for fracture [8] and fatigue crack closure [6] to prediction of surface fatigue crack growth life, it is important to have a unique material base curve $f(x)$ for straight-through fatigue crack growth rate in plates with different thicknesses. Fig. 2a shows experimental results of da/dN versus ΔK data for aluminum alloy 7075-T6 specimens with different thicknesses and stress ratios [9]. It is shown significant thickness dependence of da/dN versus ΔK curve even for the same material and stress ratio. When fatigue crack closure is taken into account according to [10–12], the da/dN versus ΔK_{eff} data for different stress ratios and specimen thicknesses fall into a unique curves with narrow scatter band as shown in Fig. 2b. The fatigue crack growth rate relation of multiple-linear segments is adopted in this paper in form of

$$\frac{da}{dN} = C_k(\Delta K_{eff})^{n_k}, \tag{2}$$

where C_k and n_k are the coefficient and power for each linear segment, $\Delta K_{eff} = K_{max} - K_{op}$, K_{max} and K_{op} are the SIF at maximum and opening loadings, respectively. As shown in Fig. 2b, the whole range of da/dN versus ΔK_{eff} data is divided into

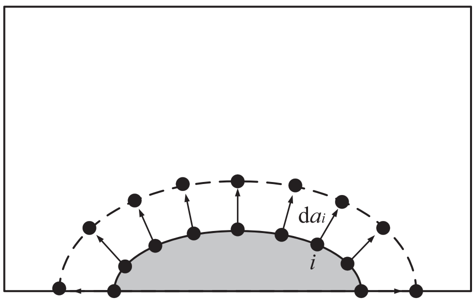

Fig. 1. Scheme of fatigue crack growth at each point of the surface crack front.